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TRIBOLOGICAL STUDIES ON DISCONTINUOUSLY REINFORCED ALUMINUM COMPOSITES BASED ON THE ORTHOGONAL ARRAYS

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ABSTRACT

The development of metal matrix composites with reinforced Aluminum composites (DRACs) represents a well-established method for improving the strength and stiffness of a material. When DRACs are being chosen for high volume and machine-intensive components, it is crucial that the tribological conditions during machining of the DRACs be understood since it is greatly different from aluminum alloys. The machinability of DRACs has been investigated actively worldwide since the 1980s, and most researchers have found that polycrystalline diamond (PCD) or cubic boron nitride tools can be used to machine DRACs effectively. Driven by the high cost of these tools, it is still desirable to optimize the cutting conditions, such as the effect of cutting fluid, since there has been no comprehensive study undertaken in this area.

This paper reports on the experimental investigations carried out under dry, oil water emulsion and steam lubricated conditions in turning of DRACs. The experiments were planned on orthogonal arrays, made with prefixed cutting parameters and different lubricated conditions. An analysis of variance (ANOVA) was carried out to check the validity of the proposed parameters and also their percentage contributions. The results of the tests show that with proper selection of the range of cutting parameters, it is possible to obtain better performance under steam lubricated condition.

Keywords: metal, aluminum, composites, arrays, DRACs, machinability.

1.0. INTRODUCTION

A Discontinuously Reinforced Aluminum Composites can be described as a material which is made up of a continuous metallic phase (the matrix) into which a second phase (or phases) has been artificially introduced. Early DRACs had their application confined to military and aerospace applications, their extensive usage was hindered due to their high production costs, limited production methods, and restricted product forms. [Evans *et al.*, 2003].

In the 1990s, [Podgorkv, 1992 and Godelvski *et al.*, 1998] proposed a new and pollution-free green cutting technique with water vapor as coolant and lubricant during cutting process .Further fluid jet assisted machining as a highly effective method for cutting of conventional materials has been well explored [Li and Seah (2001), Li (1996), Kaminski and Alvelid (2000), Hung *et al.,* (1997), Weinert (1993), Wang and Rajurkar (1997), Mazurkiewicz *et al.,* (1989), Shetty *et al.,* (2006) (2007)] in which fluids, such as air, water or steam, mainly act as transportation carriers carrying the heat away from the cutting region, and the efficiency of such a cooling method largely depends on the jet pressure. Therefore, it is necessary to understand the relationship among the various controllable parameters and to identify the important parameters that influence the quality of turning. Moreover, it is necessary to optimize [Singh and Kumar, (2004) (2005)] the cutting parameters to obtain an extended tool life and better productivity, which are influenced by tool wear and surface roughness. Design of experiment [DOE] is a statistical-based approach to analyze the influence of known process variables over unknown process variables.

Tribology plays a important role in cutting operations. Tool wear and surface finish are greatly affected by tribological conditions. The current article investigates the influence of cutting parameters and lubricating conditions on surface roughness and tool wear on turning of DRACs with Cubic boron nitride inserts (CBN) KB-90 grade.

2.0. EXPERIMENTAL PROCEDURE

2.1. Material

Al-SiC MMC work piece specimens popularly known as DRACs having aluminum alloy 6061 as the matrix and containing 15 vol. % of silicon carbide particles of mean diameter 25µm in the form of cylindrical bars of length 120mm and diameter 40mm manufactured in Vikram Sarbhai Space Centre (VSSC) Trivandrum by Stir casting process with pouring temperature 700-710°C, stirring rate 195 rpm, extrusion at 457°C, extrusion ratio 30:1, direct extrusion speed 6.1m/min to produce Ø40mm cylindrical bars. The specimens were solution treated for 2h at a temperature of 540°C in a muffle furnace, Temperatures were accurate to within ± 2°C and quench delays in all cases were within 20 s. After solutionising, the samples were water quenched to room temperature, and subsequently aged for six different times to obtain samples with different Brinell hardness number (BHN), out of which one samples were selected, one with 94 BHN obtained at peakage condition i.e. 2h at 220°C respectively. Sample selected were kept in a refrigerator right after the heat treatments. Figure-1 shows the SEM image of DRACs containing 6061 Al and 15vol. % SiC particles of 25µm.

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Figure-1. SEM image of DRACs (6061 Al/ 15% SiC 25p).

2.2. Machining test

The chemical composition of specimens is shown in Table-1. Turning method as machining process was selected. The experimental study was carried out in PSG A141 lathe (2.2 KW) with different cutting speed, feed and constant depth of cut. The selected cutting tool was cubic boron nitride inserts KB-90 (ISO code), for machining of MMC materials. The ISO codes of cutting tool insert and tool holder were shown in Table-2 respectively. The level of variables used in the experiment was given in Table-3. Surface condition of machined work piece and tool wear was observed using JEOL JSM-6380 LA analytical scanning electron microscope. Surface roughness was measured using Taylor/Hobson surtronoic 3 + surface roughness measuring instrument (Figure-2). Tool wear measurements were observed using Vision plus Tool maker microscope METZ-1395 of range from 0-25 mm, least count-10µm. Each experiment where repeated four times and four measurements of tool wear were taken from each experiment and the averages of tool wear were obtained.

Table-1. Nominal chemical composition of Base metal (6061 Al alloy).

Elements	**Cu**	**Mg**	**Si**	**Cr**	**Al**
Weight percentage	0.25	1.0	0.6	0.25	Balance

Table-2. Details of cutting tool and tooling system used for experimentation.

Tool holder specification	STGCR 2020 K-16 CTGPR 1212 F 11
Tool geometry specification	Approach angle: 91^0 Tool nose radius: 0.4 mm Rake angle: 0^0 Clearance angle: 7^0
Tool insert CBN (KB-90) specification	TPGN160304-LS

Figure-2. Roughness measurement equipment layout.

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Table-3. Levels and factors.

Levels	(A) Lubricated condition	(B) Cutting speed (m/min)	(C) Feed (mm/rev)
1	Dry	45	0.11
2	Oil water emulsions	73	0.18
3	Steam	101	0.25

2.3. Steam generator and steam feeding system.

The steam generator and steam feeding system are developed in which jet flow parameters (pressure, flow rate) and cooling distance (it is the distance between nozzle and cutting zone) are controllable. Figure-3 shows the steam generator and steam feeding system.

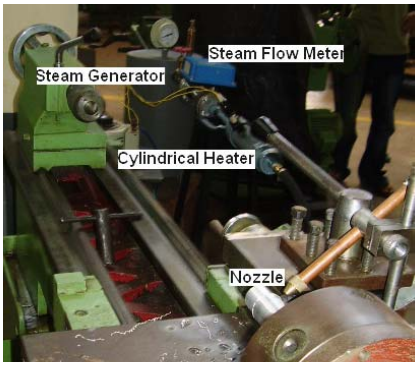

Figure-3. Steam generator and steam feeding system.

3.0. TAGUCHI's METHOD

Taguchi techniques have been used widely in engineering design [Ross (1996) and Phadke (1989)]. The main trust of the Taguchi techniques is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristic (performance measure) with minimum variation. Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. To determine the best design requires the use of a strategically designed experiment which exposes the process to various levels of design parameters.

Experimental design methods were developed in the early years of 20^{th} century and have been extensively studied by statisticians since then, but they were not easy to use by practitioners [Phadke (1989)]. Taguchi's approach to design of experiments is easy to adopt and apply for users with limited knowledge of statistics; hence it has gained a wide popularity in the engineering and scientific community. There have been plenty of recent applications of Taguchi techniques to materials processing for process optimization; some of the previous works are listed [Yang and Tarng (1998), Su *et al.*, (1999), Nian *et al.*, (1999), Lin (2002), Davim (2003), Ghani *et al.*, (2004)]. In particular, it is recommended for analyzing metal cutting problems for finding the optimal combination of parameters [Ghani *et al.*, (2004)].

3.1. Design of experiments

The orthogonal array for two factors at three levels was used for the elaboration of the plan of experiments the array L27 was selected, which has 29 rows corresponding to the number of tests (26 degrees of freedom) with 13 columns at three levels. The factors and the interactions are assigned to the columns.

The first column was assigned to the lubrication condition (A), the second column to cutting speed (B), the fifth column to the feed (C) and remaining were assigned to interactions. The output to be studied was the surface roughness and tool wear. Further, an analysis of variance (ANOVA) was carried out separately for each response.

4.0. EXPERIMENTAL RESULTS AND DATA ANANLYSIS

Figure-4 shows the comparison of surface roughness in steam application with dry and oil water emulsion. It is observed that the surface roughness is lower in steam application, compared to dry and oil water emulsion, this is because steam penetrates in to the tool chip interface decrease the chatter between SiC particulate and the alloy matrix, and avoid seizing on the flank and resulting in lower surface roughness value. From the Figure-4 it is very clear that increase in cutting speed decreases the surface roughness value in all the cases, but increase in feed certainly increases the surface roughness. Figure-5 shows the SEM images of machined surface under different lubrication condition.

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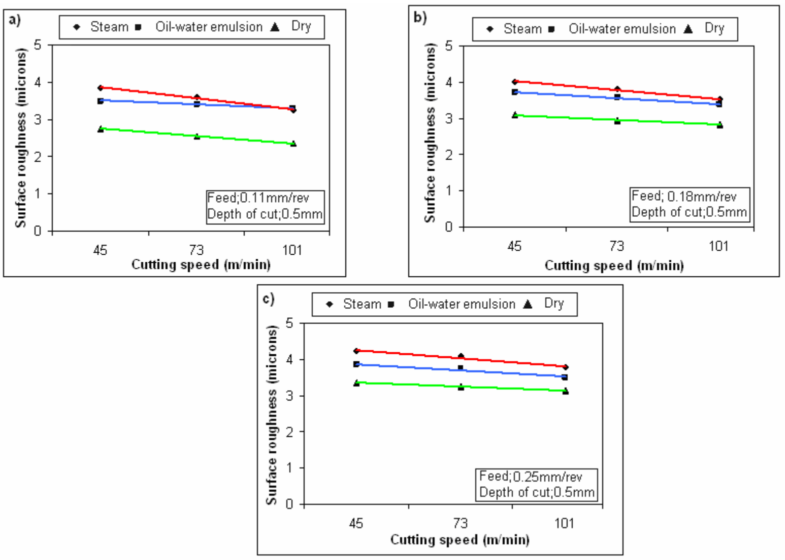

Figure-4. Variation of surface roughness with cutting speed for different lubrication conditions (a) feed (0.11mm/rev); (b) feed (0.18mm/rev); (c) feed (0.25 mm/rev).

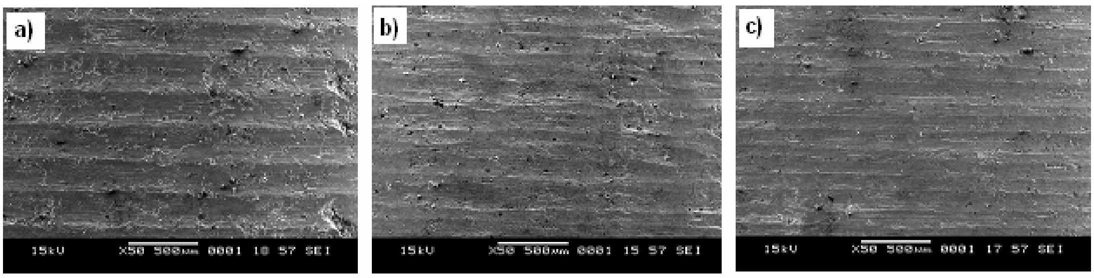

Figure-5. SEM images of machined surface under different lubrication condition (a) dry cutting; (b) oil-water emulsion; (c) steam cutting.

From Figure-6 it is very much clear that tool wear is lesser under steam jet application compared to oil water emulsion and dry cutting. This is because lubrication effect of the steam jet enables the formation of segmented type chips and more gaps appear at the chip and tool interface. This increase in gaps at the interface contributes to the higher penetrating ability of the steam and thus explains how very low tool wear readings are observed compared to oil water emulsion and dry cutting. The result obtained in Figure-6 contradicts with common expectation that tool wear usually increases with increasing cutting speed. Figure-7 shows the SEM images of flank face under different lubrication condition.

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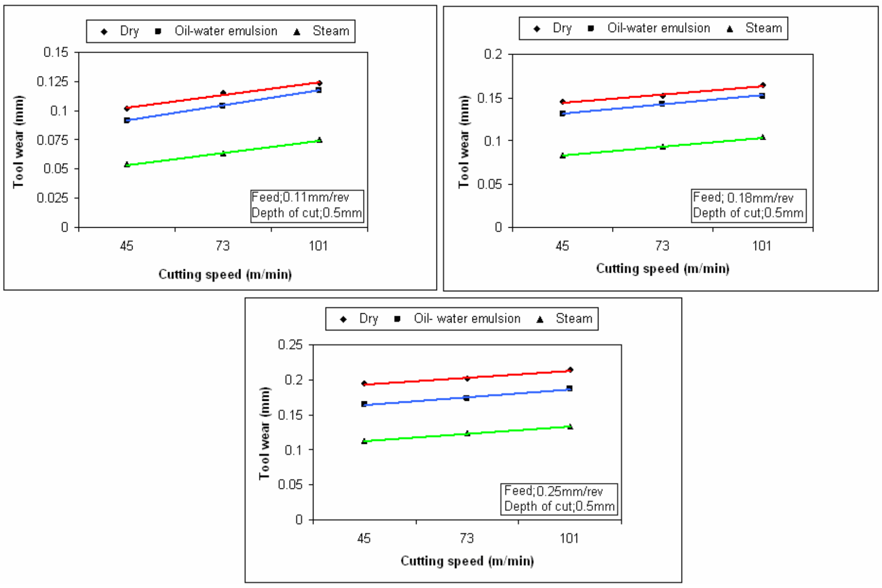

Figure-6. Variation of tool wear with cutting speed for different lubrication conditions (a) feed (0.11mm/rev); (b) feed (0.18mm/rev); (c) feed (0.25mm/rev).

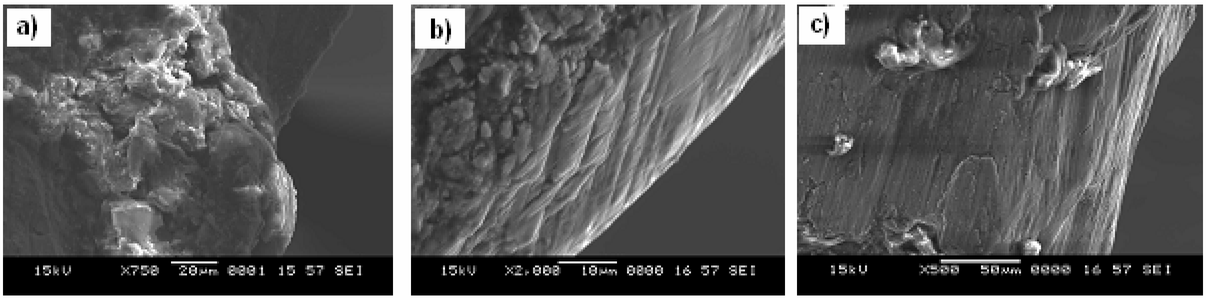

Figure-7. SEM images of flank face under different lubrication condition (a) dry cutting; (b) oil water emulsion; (c) steam cutting.

4.1. Analysis of variance (ANOVA) and factor effects

The plan of the experiment was developed for assessing the influence of the cutting speed m/min, feed rate mm/rev, and different lubrication condition on the tool wear (mm) and surface roughness (microns). Table-4 illustrates the experimental results for tool wear and surface roughness.

The experimental results were analyzed with analysis of variance (ANOVA), which is used for identifying the factors significantly affecting the performance measures. The results of the ANOVA with the tool wear and surface roughness are shown in Tables-5 and 6, respectively. This analysis was carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. Tables-5 and 6 show the P-values, that is, the realized significance levels, associated with the F-tests for each source of variation. The sources with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures. Also, the last columns of the Tables show the percent contribution of each source to the total variation indicating the degree of influence on the result.

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Table-4. Experimental results for surface roughness and tool wear.

Test No.	Lubrication condition	Cutting speed (rpm)	Feed (mm/rev)	Surface roughness (microns)	Tool wear (mm)
1	Dry	45	0.11	3.85	0.1020
2	Dry	45	0.18	4.01	0.1450
3	Dry	45	0.25	4.23	0.1940
4	Dry	73	0.11	3.60	0.1150
5	Dry	73	0.18	3.80	0.1520
6	Dry	73	0.25	4.09	0.2010
7	Dry	101	0.11	3.25	0.1230
8	Dry	101	0.18	3.53	0.1640
9	Dry	101	0.25	3.79	0.2140
10	Oil-water	45	0.11	3.50	0.0902
11	Oil-water	45	0.18	3.72	0.1310
12	Oil-water	45	0.25	3.80	0.1650
13	Oil-water	73	0.11	3.41	0.1042
14	Oil-water	73	0.18	3.57	0.1430
15	Oil-water	73	0.25	3.75	0.1740
16	Oil-water	101	0.11	3.30	0.1173
17	Oil-water	101	0.18	3.39	0.1520
18	Oil-water	101	0.25	3.51	0.1870
19	Steam	45	0.11	2.75	0.0540
20	Steam	45	0.18	3.10	0.0830
21	Steam	45	0.25	3.35	0.1120
22	Steam	73	0.11	2.55	0.0630
23	Steam	73	0.18	2.95	0.0930
24	Steam	73	0.25	3.24	0.1230
25	Steam	101	0.11	2.35	0.0750
26	Steam	101	0.18	2.83	0.1040
27	Steam	101	0.25	3.13	0.1330

On the examination of the percentage of contribution (P%) of the different factors (Table-5), for surface roughness it can be seen that lubrication condition has the highest contribution of about 67.82%, thus lubrication condition is an important factor to be taken into consideration while machining DRACs. It can be seen that feed C (P = 19.58%), cutting speed B (P = 9.99 %), and interactions A x C (P = 2.15%) have statistical and physical significance on surface roughness. The interactions (A x B, B x C) do not present a statistical significance, nor a percentage of physical significance of contribution to the surface roughness.

Table-5. Analysis of variance for S/N ratios for surface roughness.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percent P (%)
(A) Lubrication condition	2	26.1453	26.1453	13.0727	655.12	0.000	67.82
(B) Cutting speed (m/min)	2	3.8545	3.8545	1.9272	96.58	0.000	9.99
(C) Feed (mm/rev)	2	7.5512	7.5512	3.7756	189.21	0.000	19.58
A x B	4	0.2156	0.2156	0.0539	2.70	0.108	0.28
A x C	4	1.6605	1.6605	0.4151	20.80	0.000	2.15
B x C	4	0.1162	0.1162	0.0290	1.46	0.301	0.15
Residual Error	8	0.1596	0.1596	0.0200			
Total	**26**	**39.7028**					**100**

Further the examination of the percentage of contribution (P%) of the different factors Table-6, all the factors are influencing tool wear. From the ANOVA table it can be seen that feed has the highest contribution of about 49.93%, followed by lubrication condition A (P = 44.57%), cutting speed B (P = 4.92%), A x C (P = 0.23%), B x C (P = 0.21%), A x B (P = 0.14%) have statistical and physical significance on tool wear.

Table-6. Analysis of variance for S/N ratios for tool wear.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Percent P** (%)
(A) Lubrication condition	2	106.093	106.093	53.0465	3600.29	0.000	44.57
(B) Cutting speed (m/min)	2	11.703	11.703	5.8516	397.15	0.000	4.92
(C) Feed (mm/rev)	2	118.878	118.878	59.4388	4034.14	0.000	49.93
A x B	4	0.645	0.645	0.1613	10.95	0.002	0.14
A x C	4	1.108	1.108	0.2771	18.81	0.000	0.23
B x C	4	1.008	1.008	0.2520	17.10	0.001	0.21
Residual Error	8	0.118	0.118	0.0147			
Total	**26**	**239.553**					**100**

From the main effects plot Figure-8 for surface roughness indicates the selection of steam application, higher cutting speed (101 m/min) and lower feed (0.11mm/rev) result the best combination to get the lower surface roughness value during turning of DRACs.

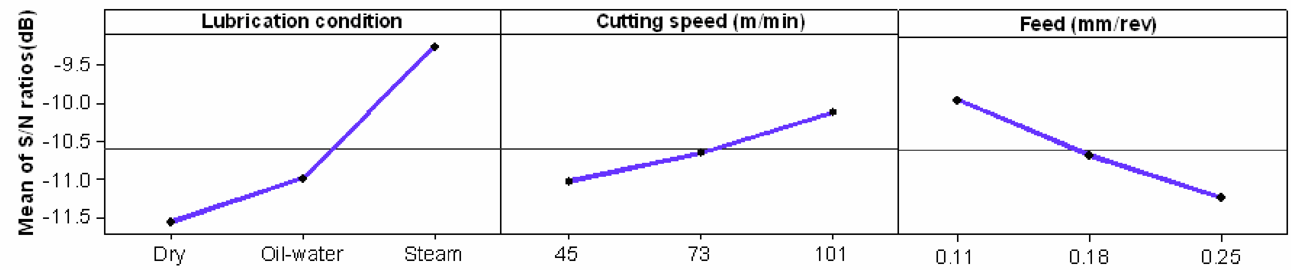

Figure-8. Mean S/N graph for surface roughness.

Further from the main effects plot Figure-9 for tool wear indicates the selection of steam application, lower cutting speed (45m/min) and lower feed (0.11mm/rev) result the best combination to get the lower tool wear value during turning of DRACs.

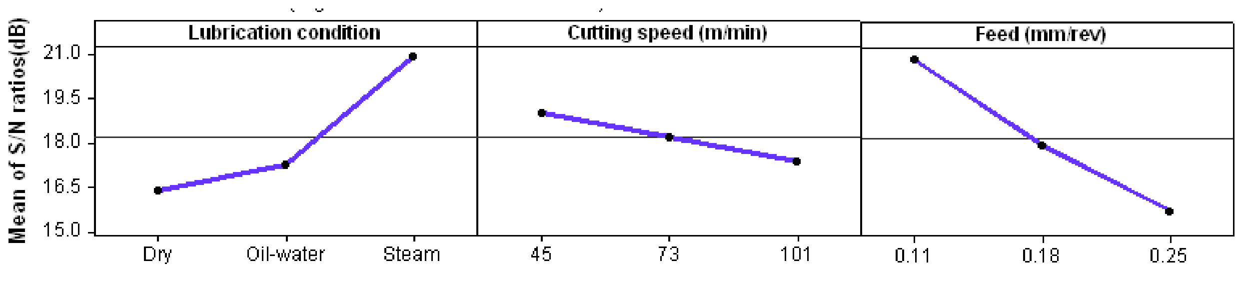

Figure-9. Mean S/N graph for tool wear.

5.0. CONCLUSIONS

The tool wear and surface roughness were studied in turning of DRACs with cubic boron nitride tool under dry, oil water emulsion and steam lubricated conditions using experimental and Taguchi's orthogonal array. From the study, it can be concluded that the steam lubrication can replace the dry and oil water emulsion if the parameters are chosen carefully. However, the process is new and much further research is needed. Based on the experimental and analytical study, the following conclusions can be drawn:

- The tool wear and surface roughness were found to be lesser for steam cutting, where as these two parameters showed much variation during oil water emulsion and dry cutting.
- The tool wears increases with increase of cutting speed and with increase in feed.
- The surface roughness decreases with increase in cutting speed and increases with increase in feed.
- The effect of lubrication condition is found to be having highest physical as well as statistical influence on the tool wear and surface roughness (67.82% and 44.57%, respectively).
- The feed is found to be the cutting parameter that affects surface roughness and tool wear of about 19.58% and 49.93%, respectively.
- The results of the study show that with a proper selection of machining parameters, it is possible to obtain a performance better in steam lubrication condition in turning of DRACs.

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